TITLE
*ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR***
EDITORS

The Impact of Galaxies on their Environment from Observations of Gravitationally Lensed QSOs

Michael Rauch

Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA 91101

Abstract. Observations of absorption systems in close, multiple lines of sight to gravitationally lensed QSOs can be used to infer the density fluctuations and motions of the gas clouds giving rise to the Lyman α forest phenomenon and to QSO metal absorption systems. We describe a survey of lensed QSOs with the Keck HIRES instrument and argue that one can derive limits on the frequency and impact of hydrodynamical disturbances inflicted by galaxies on the surrounding gas from such data. We discuss differences between the kinematic properties of low density unsaturated Lyα forest absorption systems, high ionization CIV absorption systems, and low ionization gas visible in (e.g.) SiII and CII. The general intergalactic medium (as seen in the Lyα forest) shows very little turbulence, but the presumably denser CIV systems exhibit evidence of having been stirred repeatedly (by winds ?) in the past on time scales similar to those governing stellar feedback and possibly galaxy mergers. The quiescence of the low density IGM can be used to put upper limits on the incidence and energetics of galactic winds on a cosmological scale.

1. Introduction

Historically, studying common absorption systems in the spectra of lensed QSOs was the first astrophysical application of gravitational lensing; in fact it was the presence of common absorption in the two images of 0957+561 which provided strong evidence for the lens nature of the first such system discovered (Walsh, Carswell & Weymann, 1979). Ray Weymann, in a pattern that some of the participants in this workshop may recognize, has made seminal contributions to this subject, including being the co-discoverer of the first three lensed QSOs (Walsh et al 1979; Weymann et al 1979; Weymann et al 1980; Weedman et al 1982), then to largely leave the topic for others to sort out the details - and we still are trying to after more than 20 years. There certainly has been substantial progress - I only mention here the important work by Peter Young (e.g., Young et al 1981a; 1981b) and by Alain Smette (e.g., Smette et al 1992; 1995) and their collaborators. But good spectroscopic data have been hard to obtain. The lensed images of QSOs mostly are too faint in the optical to be examined with a high resolution spectrograph; and to measure typical velocity differences in gas clouds between two lensed lines of sight (i.e., proper separations of mostly less than a few kpcs) a resolution of a few kms^{-1} is required. The advent of 8-10m class telescopes finally heralded in the post-heroic age, where such high resolution

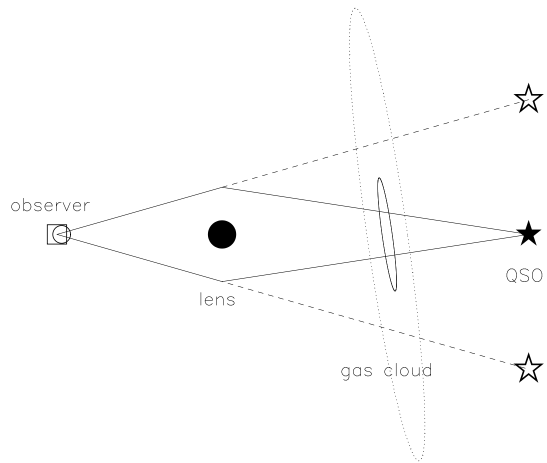

Figure 1. a galaxy lens (black dot) produces two displaced images (open star symbols) of a background QSO, which, without the lensing effect would appear as a single point source (filled star). Imagine that a gas cloud (ellipse with solid outline) is situated between the lens and the QSO causing absorption in one or both lines of sight. The angular magnification produced by the lens makes this cloud appear as if it were much bigger in projection on the sky (dotted ellipse). The higher the redshift of the cloud the smaller is the separation between the lines of sight intersecting it. Thus the combination of ground-based telescope and gravitational lens works like a gigantic microscope for the matter intervening between the lens and the QSO redshift. In practice it has been possible to study QSO absorption systems at transverse line of sight separations of a few tens of parsecs at redshifts 2-4.

QSO spectra could be obtained in a matter of hours, not days. In the present contribution I describe a survey my collaborators Wal Sargent, Tom Barlow, and I began with the HIRES instrument (Vogt et al 1984) on Keck I a few years ago. HIRES was the first instrument to allow high resolution (FWHM ~ 6 kms^{-1}) spectroscopy down to about 19th magnitude in the optical wavelength range, so several of the brightest known lenses (among them UM673 (Surdej et al. 1988; Smette et al 1992); HE1104-1805 (Wisotzki et al 1993; Smette et al 1995) and Q1422+213 (Patnaik et al. 1992; Bechtold & Yee 1995; Petry et al 1998)) and a number of other objects came within reach of having at least two images each bright enough to be examined at high resolution. The principle of using gravitational lenses to study the properties of absorption systems is illustrated in figure 1.

The differences between the absorption pattern in two adjacent lines of sight can be characterized in a variety of ways. If one thinks of the gas clouds in terms of coherent objects it makes sense to measure the optical depth or column density differences between the lines of sight, to determine the scale over which the gas densities vary and to get an idea of the cloud sizes (if the transverse beam separation is wide enough to sample these). Differences across the lines of sight of the velocities projected along the lines of sight (i.e. the velocity shear) provide clues to turbulence and systematic motion (e.g., rotation, expansion) in the gas. We have applied the relevant techniques to various classes of absorption

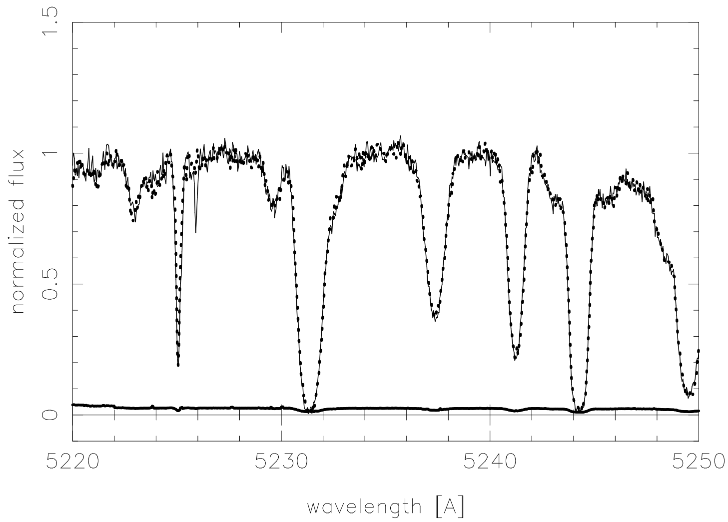

Figure 2. Enlargement of part of the spectrum of Q1422+231. The spectra of the A (solid line) and C (dotted line) images are plotted on top of each other. There is hardly any difference between the spectra, with the exception of a narrow line (which is largely absent in the spectrum of the C image) and some lower column density fluctuations near 5226 Å. This line and the sharp stronger one at 5225 Å can be identified with a SiIV 1394Å interloper from an absorption system at $z = 2.74889$. The other absorption features are plausibly attributed to HI Lyα. The slowly varying function plotted at the bottom is the $1 - \sigma$ error of image A.

systems in the abovementioned QSO spectra and describe the results below for several astrophysical environments in the order of increasing gas density.

2. The Lyman α forest

For practical purposes we restrict the term 'Lyman α forest' here to refer to absorption systems with unsaturated Lyα lines only. This distinction is based on the prejudice that such lines are mostly associated with the general intergalactic medium, as opposed to the interstellar medium or the halos of galaxies. Theoretical work and cosmological hydro-simulations show that gas condensations giving rise to such lines can be formed abundantly by gravitational collapse in hierarchical scenarios of galaxy formation. In the absence of other dynamic agents capable of stirring them up (e.g., galactic winds and explosions) these IGM clouds should be featureless on scales much smaller than the Jeans length, because of the smoothing effects of thermal gas pressure. This prediction can be tested by measuring column density and velocity differences between the lines of sight. Our spectra of Q1422+231 A and C (z_{em} =3.62) intersect the IGM at mean redshift $< z > \sim 3.3$ and at a mean separation 110 h_{50}^{-1} pc (for Lyα absorption lines between Lyβ and Lyα emission). Figure 2 shows a small section of the two spectra plotted on top of each other to demonstrate how small the differences between the two spectra are over these scales. In contrast there is a sharp narrow SiIV interloper which is very different in the two lines of sight. Metal absorption lines often look different over these separations (they are usu-

ally associated with strong, saturated Lyα lines) but the lower column density, mostly unsaturated Lyα forest lines hardly show any difference, reflecting qualitatively different astrophysical environments in the two classes of absorption systems.

2.1. By how much do the absorbers differ ?

We have fitted the whole Lyα forest with Voigt profiles using the fitting routine VPFIT (Carswell et al 1992) and determined the differences in column density and velocity between the modelled absorption components of the two lines of sight. For a subset of unsaturated Lyα lines with $12 < \log N < 14.13$, the observations show that the RMS velocity differences between the two lines of sight A and C, over a mean separation of 0.110 h_{50}^{-1} kpc, are less than

$$\sqrt{\langle (v_A - v_C)^2 \rangle} \leq 0.4\mathrm{kms}^{-1}. \tag{1}$$

The column density differences can be derived similarly. If the absorbing gas is primarily formed by gravitational collapse, the HI column density differences $\Delta N(\mathrm{HI})$ can be translated into gas density differences $\Delta\rho$ using the tight correlation $N(\mathrm{HI}) \propto \rho^{\alpha}$, with $\alpha = 1.37$ -1.5 (Schaye 2001), and the variance of the logarithmic baryon density gradient becomes

$$\left\langle (\Delta \log \rho)^2 \right\rangle \leq \alpha^{-2} \left\langle (\log N_A - \log N_C)^2 \right\rangle \tag{2}$$

or

$$\sqrt{\left\langle (\Delta \log \rho)^2 \right\rangle} \leq 3 \times 10^{-2} \tag{3}$$

for the typical logarithmic change in density over 0.110 h_{50}^{-1} kpc, i.e., the RMS fluctuations in the baryon density are less than about 3 percent.

2.2. What fraction of the Lyα forest has been disturbed ?

The above analysis depends on the identification of absorption ‘lines’ and on measuring their properties. A more general approach may involve just measuring the optical depths and comparing them for each pixel in the spectra of adjacent lines of sight. This way one could measure (e.g.) the global fraction of the Lyα forest differing by more than a certain amount in optical depth. The differences may be caused by galaxies intersecting the line of sight, or by the presence of galaxy winds or explosions stirring the IGM. Defining the ‘disturbed fraction of the Lyα forest’, or the line of sight filling factor f_{LoS} as the fraction of the spectrum where the optical depths differ by more than $\Delta\tau = |\tau_A - \tau_C| \leq 5\%$ between the lines of sight, we measure $f_{LoS} \leq 0.23$. In other words: 77% of the Lyα forest spectrum do not differ in optical depth by more than than 5% .

2.3. Limits on the volume filling factor of winds

Making some simplifying assumptions the above upper limit on the line-of-sight filling factor f_{LoS} can be translated into an upper limit on the volume filling factor of the universe for the disturbing processes, f_v. The relation between

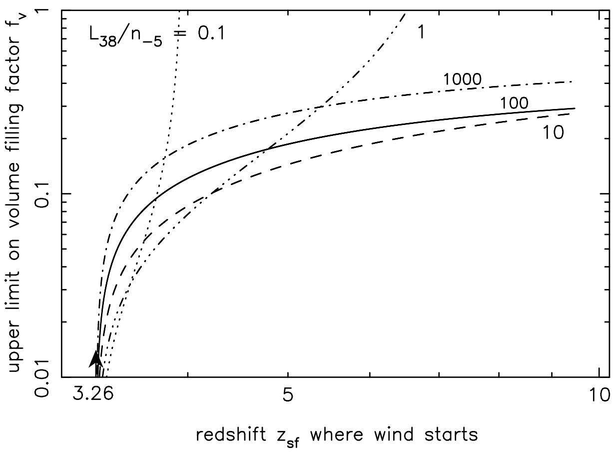

Figure 3. Upper limit on the volume filling factor for wind blown bubbles. Strong winds with $L_{38}/n_{-5} \sim 100 - 1000$ can fill a significant fraction of the volume of the universe (up to 40% in the extreme case, i.e, if they start as early as redshift 10, up to $\sim$ 18% if they start at z=4), whereas winds with $L_{38}/n_{-5} \leq 1$ are essentially unconstrained if they occur before redshift 7.

the two is of course model-dependent. If we assume that the IGM is primarily disturbed by strong spherically symmetric galactic winds and model these as superbubbles escaping from galaxies into intergalactic space, we can derive upper limits on f_v. Applying the galactic super bubble model of Mac Low & McCray (1988) we can write the volume filling factor f_v for such winds as a function of the luminosity L_{38} (in units of 10^{38} ergs/s), the density of the ambient IGM n_{-5} (in units of 10^{-5} cm^{-3}), and the time elapsed between the start of the wind and the observation. Some assumption must be made about the absorption "footprint" of a wind-driven bubble. (Rauch, Sargent & Barlow 2001b).

The results are shown in fig.3. Strong winds $L_{38}/n_{-5} \sim 100 - 1000$ are well constrained because of their long survival times; a volume filling factor of up to 40% is consistent with our upper limit on f_{LoS}, for the extreme case of $L_{38}/n_{-5} \sim 1000$ and a wind starting as early as $z = 10$. In contrast to that the absorption signature of weak winds $L_{38}/n_{-5} \sim 0.1 - 1$ is wiped out much sooner by gas pressure waves. Nevertheless, weak winds cannot venture far beyond the filaments where their parent galaxies reside and thus are unlikely to fill a substantial fraction of the voids which make up most of the universe.

3. Higher Gas Densities: Metal Absorption Systems

Going to higher densities the Lyα forest lines become saturated and invariably show simultaneous metal absorption lines, predominantly the CIV doublet. From the HI column densities it is to be expected that this gas is residing much closer to galaxies than the typical Lyα forest absorber. Nevertheless, photoionization calculations and hydro-simulations of galaxy formation show that the underlying gas density of CIV systems is mostly less than the virial density of

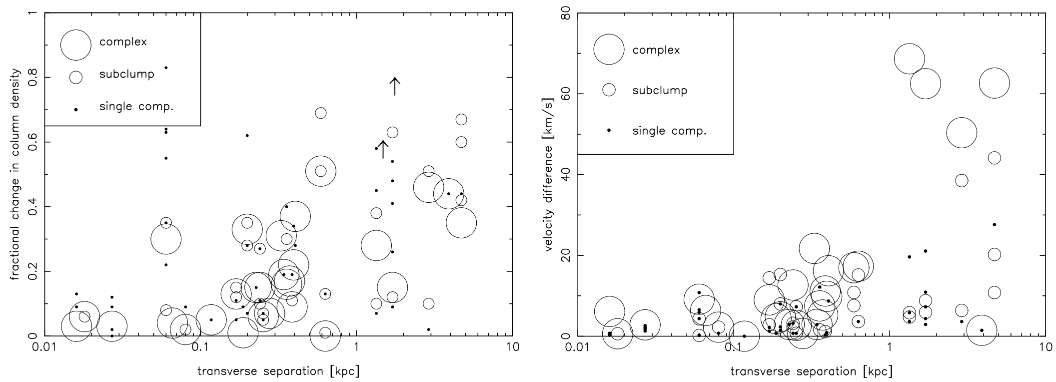

Figure 4. Fractional difference between the column densities, $(N_A - N_B)/(\max(N_A, N_B)$ (left panel) and differences between the column density weighted velocities $v_A - v_B$ (right panel) along the line of sight, versus separation between the lines of sight, for a sample of CIV systems from the three QSOs. The different symbols denote individual, "single" CIV components, subgroups of components, and absorption systems as a whole ("complex"). The arrows show lower limits (i.e., absorption at a given redshift only present in one of the two lines of sight).

a galaxy, so a typical high redshift CIV system is not directly part of a galaxy either.

We have studied CIV systems in the three lensed QSOs in regions longward of the Lyα emission line. Because of their lower source redshifts and higher lens redshifts, UM673 and HE1104-1805 provided lines of sight with wider separations than those of Q1422+231. Thus it was possible to probe CIV systems with separations up to several kpc, and to investigate how the differences between the column densities and column density weighted velocities change with the separation between the lines of sight (Fig. 4).

3.1. Cloud sizes and turbulent energy

A trend for the column densities and velocities to become more discrepant with increasing beam separation r is apparent in Fig.4. The scale where this happens defines a minimum "size" for the clouds. Both, differences in column density at the 50% level and a substantial increase in the velocity scatter appear to occur at separations on the order of a few hundred parsecs (albeit subject to a large scatter).

The existence of a minimum size for the CIV absorbers can be used to get an estimate of the frequency with which the CIV gas has been stirred up in the past. This is based on the idea that density and pressure differences in a gas cloud left alone for a certain amount of time without further disturbance from the outside would be smoothed by the effects of thermal gas pressure, and the smoothing would occur on spatial scales increasing with time. Density gradients in the CIV gas would be damped out by pressure waves propagating with the speed of sound over a spatial distance r given by the product of the sound crossing time τ_s and the sound speed, c_s. If there is little structure over

a distance r, then there cannot have been a hydrodynamic disturbance during the past

$$\tau_s \sim \frac{r}{c_s} \approx 1.4 \times 10^7 \left(\frac{r}{300\mathrm{pc}}\right) \left(\frac{c_s}{20\mathrm{kms}^{-1}}\right)^{-1} \mathrm{years}, \tag{4}$$

where a fiducial cloud size of 300 pc was assumed.

Similarly, the velocity differences between the lines of sight can be used to get an idea of the turbulent energy contents and rate of energy input into the gas. Measuring the variance in the velocity difference between the lines of sight A and B on spatial scale r, $v_r = \overline{(v_A(r) - v_B(r))^2}$ (details in Rauch et al 2001a), and applying some simple consequences of the Kolmogorov theory of turbulence, a crude estimate of the turbulent energy input ϵ into the clouds is given by $\epsilon \sim v_r^3/r \sim 10^{-3}\mathrm{cm}^2 s^{-3}$. This value is much smaller than the energy input rate in galactic starforming regions (e.g., Kaplan and Pikelner 1970), which is another indication that, by observing high redshift CIV systems, we are not usually looking straight through galaxies or starforming regions. Nevertheless the turbulence observed is finite. We can again make the argument that it cannot survive forever without further energy input. If Kolmogorov-type conditions (esp. steady state energy input) were applicable, the rate of energy input on large scales would equal the rate of dissipation on the smallest scales. Now, if the energy input were suddenly interrupted, the mean turbulent kinetic energy $1/2 < v^2 >$ would be turned into heat after a dissipation time

$$\tau_{\mathrm{diss}} \sim \frac{1}{2}\frac{< v^2 >}{\epsilon} \sim 9 \times 10^7 \mathrm{years}. \tag{5}$$

This time scale is not dramatically different from the one obtained from the minimum size of the clouds. Both estimates imply that CIV clouds are being "stirred" on a time scale significantly smaller than a Hubble time. Thus, even if the CIV gas represents, e.g., the relics of very early winds deposited by a Population III phase of stellar nucleosynthesis they must have been disturbed more recently, possibly by galactic winds or merger events. There is evidence of recurrent star formation episodes in our and other galaxies (e.g. Tomita, Tomita & Saito 1996; Hirashita & Kamaya 2000; Glazebrook et al 1999; Rocha-Pinto et al 2000) and the dynamical state of CIV clouds may reflect the effects of stellar feedback from these events upon the ambient intergalactic medium.

4. The ISM, Supernova Remnants, and Superbubbles

Occasionally, the QSO lines of sight must be looking through even denser gas in regions directly related to a galactic environment, e.g., the interstellar medium in galactic disks, gaseous halos, or expanding superbubbles. The problem is how to interpret the observed absorption pattern in terms of the physical conditions in the underlying astrophysical environment. Attempts at explaining low ionization absorption systems globally by any particular astronomical scenario have remained unconvincing (e.g., damped Lyman α systems as galactic disks). The complexity of the ISM (as seen in our Galaxy) clearly does not help here, and it is possible that local gasdynamical processes (stellar winds, supernova explosions)

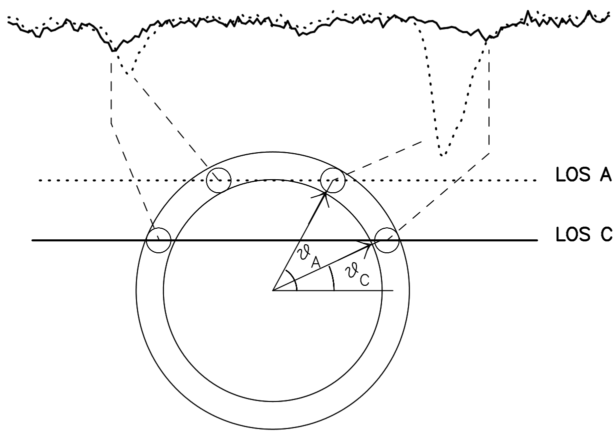

Figure 5. z=3.538 CII absorption system in the A (dotted spectrum) and C (solid spectrum) images of Q1422+231. The observed differences between the spectra include larger column densities in the A spectrum and a wider velocity spacing between the two main absorption components in the C spectrum. Such a pattern could arise in an expanding shell of gas intersected by the two lines of sight at different impact parameters.

may play a more important dynamical role than for example gravitational instability and thermal gas pressure, which are thought to be the dominant agents in the intergalactic medium.

Here we present some anectodal evidence that at least some of the low ionization absorption systems have structure on very small (pc to kpc) scales. The first example is an object observed in the spectrum of QSO 1422+231 at a beam separation of only about 26 h_{50}^{-1} pc (Rauch, Sargent & Barlow 1999).

Although it is impossible to give a unique interpretation for any given absorption system, the one discussed here (fig.5) has all the signs of arising in an evolved interstellar medium of a galaxy at redshift 3.5. The object has strong low ionization lines from CII, SiII and OI. The ionization state indicates a high density on the order of 0.1 - 2 cm^{-3}, just as in the ISM of our galaxy. The metallicity is consistent with being solar. The pattern of column density and velocity differences can be explained by the lines of sight intersecting an expanding shell of gas, possibly an old supernova remnant or bubble, with a radius $13 \leq R \leq 48$pc and an expansion velocity of $v_{\rm exp} \geq 98$kms^{-1}. In any case, since the differences between the absorption systems arise over only a few tens of parsecs the kinematics cannot reflect any large scale bulk motion of the galaxy like rotation, but must be due to a local process in the ISM.

The second case (fig.6) concerns an interesting low ionization system seen at z=0.5656 in three lines of sight to the quadruply lensed QSO 2237+0305 (Huchra et al 1985; the fourth line of sight was not observed). The system, probably damped, shows strong MgII, FeII, and MgI lines, in particular a central pair of lines, which seems to expand in velocity space as one goes from A to C to B in order of increasing distance from A. This can be explained in a model where all three lines of sight are looking through the same, expanding bubble of gas, and each of the intersections with the bubble wall gives rise to an absorption

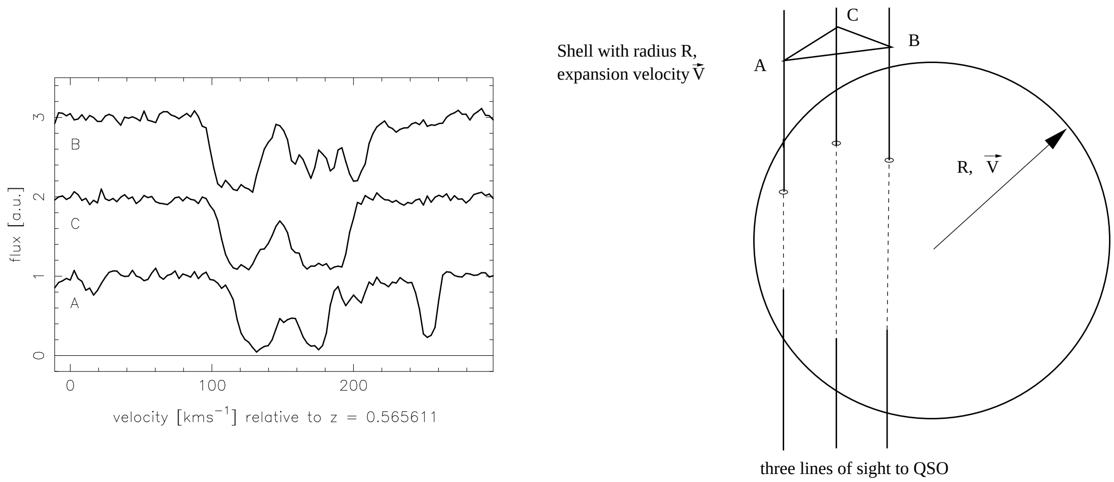

Figure 6. left: MgII structure in the three lines of sight (A, B, C) to Q2237+0305, Right: bubble model, showing the possible geometry.

component. Again, such an explanation is not unique, of course. However, the plausibility of an identification of MgII systems with expanding superbubbles has also recently been advocated on other grounds by Bond et al (2001).

5. Conclusions

We have argued that evidence for gasdynamical processes at high redshift, including the effects of stellar feedback on the intergalactic medium can be found (or at least sought) by probing space with multiple closely spaced lines of sight to gravitationally lensed QSOs. There is little evidence for disturbances in the low density Lyman α forest, and simple models indicate that it may be hard to fill a dominant fraction of the volume of the universe with winds and not notice them as small scale disturbances in the Lyα forest.

However, the saturated Lyα systems and high ionization metal absorption lines in general do show signs of energy input on scales down to a few hundred parsecs. The degree of difference between the lines of sight allows us to estimate how long ago the energy input must have occured. The CIV gas in particular appears to be loosely associated with galaxies, and seems to repeatedly have been influenced by galactic feedback.

Relatively little is known about the small scale properties of low ionization gas, but the few systems studied are consistent with having structure at least down to a scale of 10 pc, where CIV gas clouds are almost always homogeneous. It appears that we are seeing gasdynamical processes in the interstellar medium or gas bubbles that have been blown off their parent galaxies and may be sweeping up matter from the ambient intergalactic medium.

I thank Wal Sargent, Tom Barlow, and Bob Carswell for allowing me to present our results at this conference, and Bob Carswell again for useful comments on the manuscript.

References

Bechtold, J., Yee, H.K.C. 1995, AJ, 437, 83

Bond, N.A., Churchill, C.W., Charlton, J.C., Vogt, S.S., 2001, ApJ, 557, 761

Carswell, R.F., Webb, J.K., Cooke, A.J., Irwin, M.J., 1992, Institute of Astronomy, Cambridge, http://www.ast.cam.ac.uk/rfc/vpfit.html

Glazebrook K., Blake C., Economou F., Lilly S., Colless M., 1999, MNRAS, 306, 843

Hirashita H., Kamaya H., 2000, ApJ, 120 728

Huchra, J., Gorenstein, M., Kent, S., Shapiro, I., Smith, G., 1985, AJ, 90, 691

Kaplan, S.A., Pikelner, S.B., 1970, The Interstellar Medium (HUP)

Mac Low, M.-M., McCray R., 1988, ApJ, 324, 776

Patnaik,A.R., Browne, I.W.A., Walsh, D., Chaffee, F.H., Foltz, C.B., 1992, MNRAS, 259,1

Petry, C.E., Impey, C.D., Foltz, C.B., 1998, ApJ, 494, 60

Rauch, M., Sargent, W.L.W., Barlow T.A., 1999, ApJ, 515, 500

Rauch, M., Sargent, W.L.W., Barlow T.A., 2001a, ApJ, 554, 823

Rauch, M., Sargent, W.L.W., Barlow T.A., Carswell, R.F., 2001b, ApJ, in press

Rocha-Pinto H.J., Scalo J., Maciel W.J., Flynn C., 2000, ApJ, 531, L115

Schaye, J., 2001, ApJ, in press

Smette, A., Surdej, J., Shaver, P. A., Foltz, C.B., Chaffee, F.H., Weymann, R.J., Williams, R.E., Magain, P., 1992, ApJ, 389, 39

Smette, A, Robertson, J.G., Shaver, P.A., Reimers, D., Wisotzki, L., Koehler, T., 1995, A&AS, 113, 199

Surdej, J., et al. 1988, A&A, 198, 42

Tomita A., Tomita Y., Saito M., 1996, PASJ, 48, 285

Vogt, S.S. et al, 1994, Proc, SPIE, 2198, 362

Walsh, D., Carswell, R.F., Weymann R.J., 1979, Nature, 279, 381

Weedman, D.W., Weymann, R.J., Green, R.F., & Heckman, T.M., 1982, ApJ, 255, L5

Weymann R.J., Chaffee, F.H., Davis, M., Carleton, N.P., Walsh, D., & Carswell, R.F., 1979, ApJ, 233, L43

Weymann R.J., Lastham, D., Angel, J.R.P., Green, R.F. Liebert, J.W., 1980, *Nature*, 233, L43

Wisotzki,L., Köhler, T., Kayser, R., Reimers, D., 1993, A&A, 278, 14

Young, P., Deverill, R.S., Gunn, J.E., Westphal, J.A., Kristian, J., 1981, ApJ, 244, 756

Young, P., Sargent, W.L.W., Boksenberg, A., Oke, J.B.,, Gunn, J.E., 1981, ApJ, 249, 415